EFFICIENT ACCELERATING STRUCTURES FOR LOW-ENERGY LIGHT IONS*

S.S. Kurennoy#, L.J. Rybarcyk, and T.P. Wangler, LANL, Los Alamos, NM 87545, U.S.A.

Abstract

The radio-frequency quadrupole (RFQ) accelerator is the best structure immediately after an ion source for accelerating light-ion beams with considerable currents. On the other hand, the higher-energy part of the RFQ is known to be not a very efficient accelerator. We consider alternative room-temperature RF accelerating structures for the beam velocities in the range of a few percent of the speed of light – including H-mode cavities and drift-tube linacs – and compare them with respect to their efficiency, compactness, ease of fabrication, and overall cost. Options for the beam transverse focusing in such structures are discussed. Possible applications include a compact deuteron-beam accelerator up to the energy of a few MeV for homeland defense.

INTRODUCTION

Applications in homeland defense include deuteron beams of energy 4 MeV with the peak current of 50 mA and duty factor of 10%. One option to deliver such beams is a 4-MeV radio-frequency quadrupole (RFQ) accelerator. It is recognized, however, that the higher-energy RFQ section is not the most efficient accelerator: the RFQ shunt impedance $Z_{sh}T^2$ decreases as β^{-2} [1, 2]. Therefore, exploring alternatives is worthwhile.

At very low beam velocities the RFQ is required to bring the deuteron beam to about 1 MeV while providing its bunching and transverse focusing. Assuming that, we will consider alternative structures for the beam velocity range of β = 0.034-0.065 corresponding to the deuteron kinetic energy from 1 MeV to 4 MeV. We also restrict ourselves to room-temperature (RT) structures only (to assure the system mobility and ease of use) and assume the RF frequency around 200 MHz, which is in the range of both the 4-rod and 4-vane RFQ designs. High RF losses exclude λ/4- and λ/2- structures which are very efficient in low-energy superconducting (SC) accelerators for heavy ions. Remaining options include the venerable drift-tube linac (DTL) and H-mode structures: IH (Inter-digital H) and CH (Cross-bar H, topologically similar to the spoke cavities), see recent review [3]. Table 1 lists their typical parameters in the low beam-velocity range; the data are compiled mainly from [1-3]. For RFQ, the shunt impedance is usually not cited; simple calculations give 2.6 MΩ/m for the SNS RFQ. The average value of $Z_{sh}T^2$ for the first tank in the LANSCE DTL (β = 0.04-0.105) is 28.6 MΩ/m [3]. From these data one can expect that IH structures are an order of magnitude more efficient than DTL and RFQ at low beam velocities, β = 0.03-0.1.

* This work was supported by the US Department of Energy under Contract Number DE-AC52-06NA25396

#kurennov@lanl.gov

Table 1: Parameters of low-energy accelerating structures

Struct.	"Best" β	f, MHz	$Z_{sh}T^2$, MΩ/m
RFQ	$0.005 \le \beta \le 0.03$	4-rod: $10 \le f \le 200$ 4-vn: $100 \le f \le 425$	$\approx 1 - 3$; $\sim \beta^{-2}$
IH	$0.01 \le \beta \le 0.1$	$30 \le f \le 250$	300 → 150
CH	$0.1 \le \beta \le 0.4$	$150 \le f \le 800$	150 → 80
DTL	$0.1 \le \beta \le 0.4$	$\beta\lambda$: $100 \le f \le 500$	25 – 50

In the DTL structure the transverse beam focusing is provided by quadrupole magnets placed inside its large drift tubes (DT). These are usually electromagnetic quadrupoles (EMQ) but sometimes permanent magnet quadrupoles (PMQ) are used, e.g. in the SNS DTL. In the H-mode structures the DT transverse sizes are much smaller than in DTL. One approach to achieve transverse focusing in H-structures has been provided by special focusing insertions – e.g. quad triplets [4] – either placed inside or between the tanks. However, such insertions significantly reduce the effective accelerating gradient. The alternative phase focusing keeps the H-structure efficiency but it is better suited for low-current (medical) applications, see [5]. The use of RF electric focusing has been developed and implemented for both the IH [6, 7] and for DTL [8]. These methods use DTs configured as separate pieces that create a focusing gap with a four-finger geometry. We propose to install compact PMQs inside the small drift tubes in the IH structure. This solution preserves the high shunt impedance of the H-mode structures but, because the DTs are small, it requires a careful balance of the accelerating efficiency, transverse beam focusing, and the structure thermal management.

STRUCTURE COMPARISON

We compare the H-mode and DTL structures at the low-energy (β=0.034) and high-energy (β=0.065) ends of the deuteron accelerator by modeling their performance with the CST MicroWave Studio (MWS). All structures operate at the same RF frequency 201.25 MHz and have the same period, L = 5.04 cm at the low-energy end – it includes two DT for H-cavities and one for DTL, cf. Fig. 1. The gap length is 0.15 of the cell length, and the DT bore (aperture) radius is 0.5 cm. The DT outer radius is chosen to be 1.1 cm for H-structures and 2 cm for DTL. The computation results are compared in Tab. 2, where field-dependent values are calculated for the average on-axis field E_0 = 2.5 MV/m. There R is the cavity inner radius; the maximal surface power density $(dP/ds)_{max}$ and power loss per period P_{loss} are given for 100% duty assuming a copper surface. One period of each structure is illustrated in Fig. 1. The lengths of all cavity slices in Fig. 1 are the same but the transverse sizes are different, cf. R in Tab. 2. The transit-time factors T are close to 0.9 for all H-types in Tab. 2 and equal to 0.816 for the DTL. Note that the radius of the DTL structure is 4-5 times larger than in H ones. Moreover, the H-mode structures distribute the surface currents more evenly. All that reduces the power losses and makes them much more efficient compared to DTL at these velocities. The vanes in H-cavities reduce the area of the regions of high power loss density on stems – compare Figs. 1 (a) and (b) – and increase the structure efficiency even more.

Table 2: Structure comparison at $\beta = 0.034$

Struct.	***R*, cm**	**$Z_{sh}T^2$, MΩ/m**	**$(dP/ds)_{max}$, W/cm²**	**P_{loss}, kW**	**E_0TL, kV**
IH	9.9	294	7.30	0.87	113.4
IH_{vanes}	10.4	346	5.88	0.74	113.4
CH	16.4	227	4.60	1.13	113.4
DTL	55	21.5	31.1	9.74	102.0

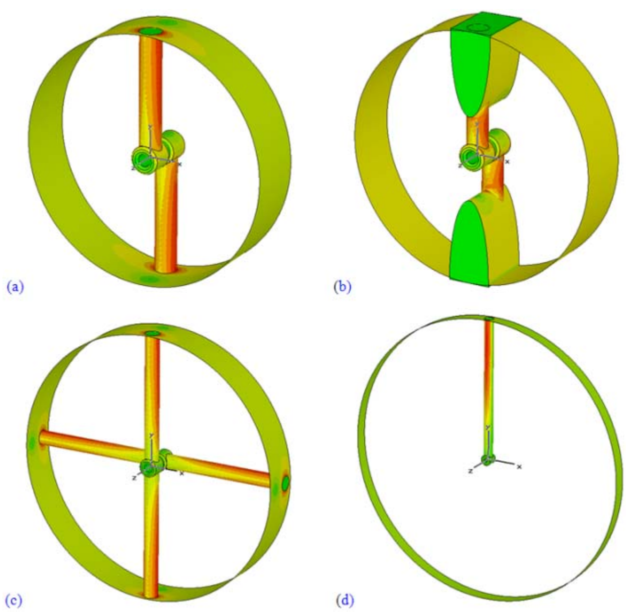

Figure 1: Surface current distributions for the structures in Tab. 2: (a) IH; (b) IH with vanes; (c) CH; and (d) DTL. Red means high current density, green – low. The spatial and current scales are different in all pictures, cf. Tab. 2.

The structure comparison for $\beta = 0.065$ is presented in Tab. 3 and Fig. 2. The period is the same for all structures here, $L = 9.64$ cm. The DT outer radius is still 1.1 cm for H-structures, but it was increased to 3.5 cm for DTL to keep the max power density reasonable. The transit-time factors T are about 0.96 for all three H-structures in Tab. 3 and equal to 0.87 for the DTL. Comparing Tab. 2 and 3, we see that at the higher beam-velocity, around $\beta = 0.065$, the efficiency increases for the DTL but decreases for H-structures. Still, at these beam velocities H-mode structures remain a few times more efficient than the standard DTL, as evidenced by the values in Tab. 3.

Table 3: Structure comparison at $\beta = 0.065$

Struct.	***R*, cm**	**$Z_{sh}T^2$, MΩ/m**	**$(dP/ds)_{max}$, W/cm²**	**P_{loss}, kW**	**E_0TL, kV**
IH	13.4	217.1	17.6	2.54	230.8
IH_{vanes}	14.0	269.3	17.7	2.04	230.4
CH_{van}	20.0	133.6	8.2	4.1	230.6
DTL†	52.9	33.8	18.8	13.4	209.0

† The aperture radius is 0.75 cm in the DTL case; DT transverse size is adjusted to reduce the maximal loss power density.

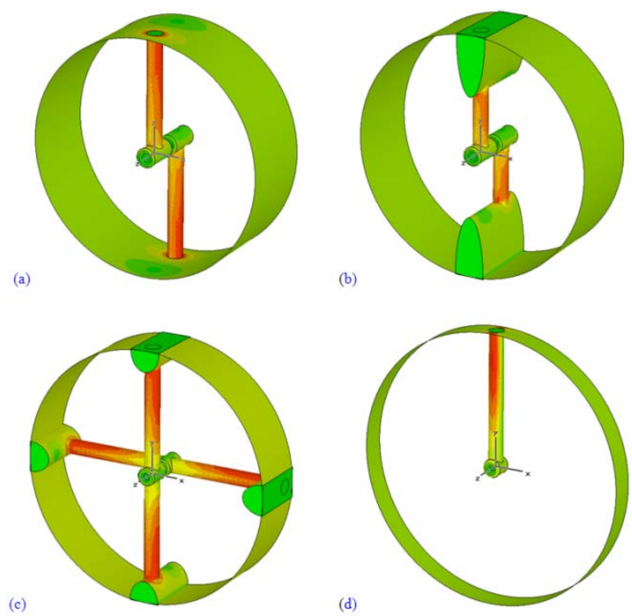

Figure 2: Surface current distributions for the structures in Tab. 3: (a) IH; (b) IH with vanes; (c) CH with small vanes; (d) DTL. See Tab. 3 for spatial and current scales.

One should mention that the accelerating structures presented in Tab. 2-3 and Fig. 1-2 are not optimized. One can adjust their parameters like drift tube, stem, or vane sizes to further improve their characteristics. Important to note that increasing the outer diameter of DT in H-mode structures reduces the shunt impedance significantly; the DTL, however, is not very sensitive to this change. On the other hand, the H-structures are less sensitive to the change of the aperture size than DTL. As an example of how the IH-structure efficiency can be increased by changing the vane and stem shape and the DT transverse sizes, Fig. 3 shows one period of a modified IH structure with vanes for $\beta = 0.034$. Its shunt impedance, 746 MΩ/m, is more than double the best value in Tab. 2. For a fair comparison, the DT outer radius is only 0.75 cm and the bore radius is 0.3 mm in this case. Of course, it would be very difficult to provide the transverse beam focusing in this structure since a strong PMQ needs to be placed inside such a tiny DT. We have to study the beam dynamics in the structure within practical limitations imposed by the existing PMQs and the requirements of the structure cooling.

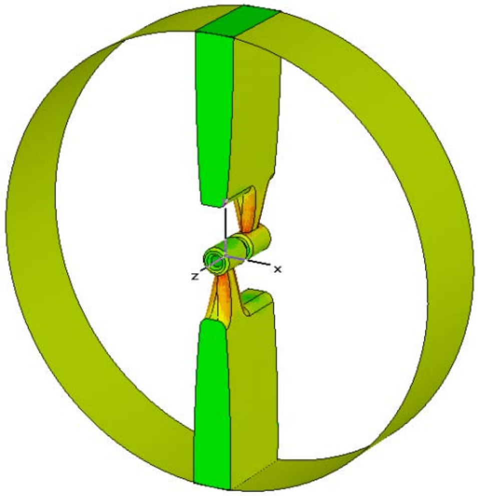

Figure 3: Surface current distribution for the modified IH structure with vanes at $\beta = 0.034$, with $Z_{sh}T^2 = 746$ MΩ/m.

PMQ FOCUSING IN H-STRUCTURES

Preliminary simulations of the beam dynamics in IH-structure show feasibility of the PMQ beam focusing in our application even at $\beta = 0.034$, where the magnetic focusing is the most difficult due to the shortest DT length and the lowest beam velocity. Beam dynamics runs with TRACE 3-D demonstrate that a deuteron beam having a rather high current, 50 mA, can be focused well within the aperture by placing a PMQ with a gradient of 200 T/m inside only every third DT. Such PMQ gradients are easily achievable using permanent Samarium-Cobalt (SmCo) magnets with a rather typical value of the residual induction, around 1 T. The PMQ length was taken to be 2 cm to fit inside 2.16-cm long DT; the PMQ inner diameter was 1 cm and outer diameter 2.2 cm.

This result gives us some options. One is to reduce the outer diameter of those DTs that do not have PMQ inside, to increase the overall structure efficiency. Another option is using weaker PMQs in all or every other DT to improve the focusing and have additional flexibility for matching the beam to other structures. The choice should be based on trade-off study following beam dynamics simulations.

ENGINEERING CONSIDERATIONS

Important engineering challenges need to be addressed in H-structures with PMQ focusing. The most important is the structure cooling: it must be both simple (without water channels inside DT, to keep the DT size small) and efficient to ensure that the DT heating is not excessive, so that the DT temperatures do not exceed the maximal working temperature of the permanent magnets, 200-250°C. Due to high accelerating efficiency, the system overall heat load will be lower than in the RFQ or DTL, so its cooling with chilled water should be simpler. A cooling system design with cooling channels inside the vanes seems attractive and feasible but a detailed thermal and stress engineering analysis has to be performed to make sure that the temperature distribution is acceptable.

Another engineering aspect, the structure fabrication, can be also simple, especially for the IH structures. A modular design, with the DTs mounted on two separate vanes, looks rather appealing.

APPLICATIONS

For a compact 4-MeV deuteron-beam accelerator used in an intense neutron and gamma source for interrogation of nuclear materials in cargo, IH-type structures with PMQ focusing after a short RFQ offer a simple and effective solution. The total number of cells in such an accelerator will be less than 40 (20 IH periods), covering the β-range 0.034 to 0.065, with the total cavity length less than 1.3 m, assuming the accelerating gradient 2.5 MV/m. The required RF power for the whole cavity is estimated to be below 35 kW at 100% duty with practical values of copper conductivity; the beam power is 50 mA · 3 MV = 150 kW CW. At 10% duty, the required RF power is about 4 kW for the structure plus 15 kW for the beam, which is less than 20 kW total. In this power range, there is an option of using IOTs as RF power generators.

IH-based room-temperature accelerating structures can also be considered as a possible effective replacement for the aging DTL front end in the LANSCE linac.

CONCLUSION

The room-temperature RF accelerating structures based on H-mode resonators with the PMQ transverse beam focusing – which would follow a short, low-energy RFQ – appear to be an effective option for the beam velocities in the range of a few percent of the speed of light. They compare favorably to the usual DTL and RFQ structures with respect to their efficiency, compactness, ease of fabrication, and, likely, overall cost.

We plan to explore the room-temperature H-mode structures in more details. Achieving a balance of the structure efficiency, beam quality, and thermal management will require multiple iterations of electromagnetic modeling, beam dynamics, and engineering thermal-stress analysis.

The authors would like to acknowledge useful discussions with D. Barlow and J. O'Hara of LANL.

REFERENCES

[1] A. Chao, M. Tigner (Eds.), *Handbook of Accelerator Physics and Engineering*, World Sci., 1999 & 2006.
[2] T.P. Wangler, *Principles of RF Linear Accelerators*, J. Wiley & Sons, NY, 1998.
[3] H. Podlech, LINAC04, Lübeck, 2004, p. 28.
[4] U. Ratzinger, NIM A464 (2001) 636.
[5] Y. Iwata et al., NIM A566 (2006) 256.
[6] V.A. Teplyakov, LINAC92, Ottawa, CA, 1992, p. 21.
[7] D.A. Swenson et al., PAC03, Portland, OR, 2003, p. 2889.
[8] D.A. Swenson, LINAC94, Tsukuba, 1994, p. 804.

